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THE ORIGINS OF NUCLEAR ASTROPHYSICS AT CALTECH

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ABSTRACT

Shortly before the start of World War II, several theoretical physicists, including Hans Bethe and Carl von Weizsäcker, advanced the idea that the sun derives it energy from nuclear reactions within its core. C. C. Lauritsen and William Fowler, nuclear physicists at Caltech's Kellogg Laboratory, were among the first experimentalists to appreciate the application of nuclear physics to stellar interiors. Post-war strategies for studying nuclear processes in the stars included an innovative series of unofficial, weekly seminars with Mt. Wilson astronomers at director Ira Bowen's house, the testing of Bethe's carbon cycle in Kellogg, and the collaboration with a diverse group of scientists ranging from cosmologist Fred Hoyle to astronomers Margaret and Geoffrey Burbidge. The events leading up to the publication of the 1957 paper by Fowler, Hoyle, Burbidge, and Burbidge, in The Reviews of Modern Physics, now regarded as a watershed in the history of nuclear astrophysics, are discussed. For his work in low-energy nuclear astrophysics, Fowler won the 1983 Nobel Prize in physics.

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Subjects ranging from physical chemistry and geophysics at the turn-of-the century, to biophysics and applied mathematics in more recent times, have successfully bridged several disciplines and become independent enterprises.[1] Nuclear astrophysics, the offspring of the marriage of nuclear physics and astronomy, is a case in point.

Caltech's Kellogg Radiation Laboratory pioneered the application of nuclear physics to astrophysics problems. Shortly before the start of World War II, several theoretical physicists, including Hans Bethe at Cornell and Carl von Weizsäcker in Germany, advanced the idea that the sun derives its energy from nuclear reactions within its core. To Caltech nuclear experimentalists C. C. Lauritsen and his student William Fowler, the suggestion about where the energy came from in stars crowned six years of intensive study of the excited states in the nuclei of the light elements listed in the periodic table. Lauritsen's group learned about Bethe's work early in 1938 through Robert Oppenheimer, who was then dividing his time between UC Berkeley's physics department and Caltech's. "For those of us in Kellogg," Fowler later recalled, "this was a dramatic event in our lives. What we were doing in the lab had something to do with the stars."[2]

Pearl Harbor abruptly ended Kellogg's peacetime basic research program, and with it any chance of Lauritsen and Fowler following up Bethe's theoretical ideas. Post-war strategies for studying nuclear processes in the stars included a series of informal, weekly seminars with Mt. Wilson astronomers at director Ira Bowen's house, the testing of Bethe's carbon-nitrogen cycle in Kellogg's laboratory, and Fowler's collaboration with a diverse group of scientists ranging from cosmologist Fred Hoyle to astronomers Margaret and Geoffrey Burbidge. In 1957, the four published a comprehensive account of their work in Reviews of Modern Physics. Still a classic paper in the field, "Synthesis of the Elements in Stars" at once marked the successful passage of nuclear astrophysics from adolescence to maturity.

The story of Kellogg's role in this work dates back to the early thirties, when Caltech's Lauritsen, Carnegie's Merle Tuve, and Berkeley's Ernest Lawrence were the three big names in American experimental nuclear physics. The Tuve-Lawrence-Lauritsen correspondence preserved at the Library of Congress, the Bancroft Library and the Caltech Archives lends substance to local oral testimony that the three laboratories ran on thinly-camouflaged institutional rivalries, intense scientific competitiveness, and a healthy dose of respect.[3] Above all, the letters are a reminder that Caltech was at the cutting edge of nuclear physics within six months of the original artificial-disintegration-of-nuclei experiments of Cockcroft and Walton at the Cavendish in 1932.

"Lauritsen's qualifications in nuclear physics are obvious," Tuve said of his Pasadena colleague in 1937, several years after the three laboratory leaders had carved out rather different research programs. By then, the scientists had largely buried their differences, as well as the urge to rush into print first, right or wrong. Lauritsen had the ability to "work his men very hard and make them love it," he added.[4] Tuve did not exaggerate.

The Kellogg Laboratory, built in 1931 with funds supplied by Detroit cornflake magnate, W. K. Kellogg, led a double life for much of the thirties. By day, C. C. Lauritsen's students operated and maintained the high potential x-ray tube used to treat cancer patients; by night they studied proton, deuteron, and helium-ion interactions with carbon, lithium, beryllium, and boron nuclei. By 1939, the cancer research treatment had run its course, the doctors and medical technicians had left, and the nuclear research that Lauritsen had cultivated and protected during the depression years took over Kellogg.[5]

From the start, the Kellogg group concentrated on the nuclear disintegrations and atomic transformations of carbon and the other light elements. An accomplished structural and architectural engineer, the versatile Danish-born Lauritsen excelled in designing simple, straightforward, and elegant experiments. The group's initial experiments consisted of making transformations from one element to another; to do this, they had to design and build high-voltage accelerators, and develop ion sources and detection equipment. Lauritsen's sensitive electroscopes became the industry's standard. In

1934, Tuve challenged in print the results from one of Lauritsen's experiments; Lauritsen simply sent him one of his meters and suggested he measure the rate of radioactivity again. Not long after, Tuve apologized and published a retraction.[6]

Lawrence's equivocal attitude towards Caltech and the Kellogg research group permeates the letters he wrote to Tuve, a childhood friend and then, in 1923, a fellow graduate student at the University of Minnesota. Ten years later, in 1933, Tuve and Lauritsen were in a race to produce artificial neutrons with accelerators. Lawrence knew what was going on in Pasadena, because Oppenheimer divided his time between Berkeley and Caltech. On February 9, 1933, Lawrence wrote to Lauritsen, congratulating him on the production of neutrons. "From Robert Oppenheimer's account of your work, there can be little doubt that you are actually detecting neutrons. I understand also that Tuve in Washington has gotten plenty [of] good evidence of neutrons produced by 600 kilovolt helium ions."[7] While praising his work, Lawrence wasn't about to concede the definitive discovery to Lauritsen yet.

Lawrence told Tuve as much. In a letter to the Washington scientist dated 18 February, nine days later, he complained about Millikan's influence with the press. "I have noticed a report in 'Science Service' that Lauritsen has produced neutrons, and the usual Caltech ballyhoo is set forth regarding his being the first in the country, etc., to do it." And he urged Tuve to publish his own findings quickly, saying, "Despite the Science Service report it appears that you are the first one to accomplish it." Tuve knew better. At the end of March, he wrote Lauritsen that he had made an extensive search for neutrons, all "with negative results."[8] Even so, Lauritsen refined and repeated the experiments again and again before sending the paper announcing his discovery of artificial neutrons to Physical Review in September of 1933.

The historical connection between Kellogg's experimental work and Bethe's deduction that fusion powers the sun and the stars turns on a discovery made by Lauritsen and his graduate student Dick Crane in 1934. Lauritsen and Crane bombarded carbon 12, the most abundant of the carbon isotopes, with protons, and to their surprise, the nuclei did not disintegrate--or so it seemed. When the proton bombarding energy exceeded 650 kev, they observed radioactive nitrogen 13 and gamma radiation instead. But Lauritsen waged a lonely battle in the beginning; few physicists, Oppenheimer included, were prepared to believe in 1934 that a particle could be added to a nucleus without some other particle being spun off to carry away the excess energy. Tuve, in fact, had quarrelled publicly with Lauritsen's findings, attributing his observations to natural deuterium contamination. When Lauritsen pressed him to repeat the experiment, Tuve replied, "OK, Charlie, lend me one of your electroscopes."[9] This time, Tuve and his collaborator Lawrence Hafsted also found the narrow peaks, called resonances, in the excitation curves for the proton-induced activity.

The proton-carbon excitation curves bore little resemblance to the smooth and continuous reaction-rate curves associated with deuteron energy. "This marked difference in excitation curves," Fowler later wrote, "convinced Lauritsen and Crane that protons did indeed produce nitrogen 13 in carbon bombardment."[10] The reaction Fowler described is an example of a process known as radiative capture. In this process, the projectile is captured by the nucleus and forms an excited state of a new isotope, or element, which then decays to its ground state by radiating a gamma ray. It is "resonant" because the projectile must have just the right energy to form the excited state of the new species.

The discovery of radiative capture of protons by carbon fixed Kellogg's nuclear physics program for the rest of the decade. Convinced that the excitation levels in the light nuclei were the key to understanding the structure of the nucleus, Lauritsen and his students undertook detailed measurements of nuclear reaction rates of all the light nuclei. Fowler received his doctorate in 1936, and for the next three years, he and Lauritsen spent much of their time studying excitation curves, the yield of the activity produced versus energy, for the carbon and nitrogen isotopes bombarded with protons.

At the end of the decade, Bethe suggested that the thermonuclear reactions underlying the conversion of hydrogen into helium in the stars depends in a crucial way on a catalytic process known as the carbon-nitrogen cycle.[11] In the first of the six nuclear reactions involved in the transformation cycle, a nucleus of carbon 12 fuses with a proton or hydrogen nucleus to yield a nucleus of nitrogen 13 and a gamma ray. Bethe's first reaction in the cycle matched exactly Lauritsen's 1934 laboratory reaction.

The controversy over the discovery of the radiative capture of protons by carbon 12 was still fresh in Lauritsen and Fowler's mind when news of Bethe's carbon-nitrogen cycle reached them. "When Bethe came out with the carbon-nitrogen cycle, we kind of felt a proprietary interest in this group of reactions," Fowler recalls, "because we had been working on them . . . [it] all tied very closely together."[12] By then, the Kellogg researchers had switched from an alternating-current high-voltage tube to a 2-MeV direct current electrostatic accelerator, capable of high resolution work. With the new Van de Graaff machine, Lauritsen and Fowler had begun to measure very carefully all the effects associated with resonance phenomena. Experimental work on reaction-rates at resonance, locations and widths of resonances, and gamma-ray spectra at low energy in the light elements boomed. For the first time, they were in a position to do very careful excitation curves -- and only by accurately measuring nuclear reaction rates could problems such as Bethe's application of nuclear physics to astronomy be solved.

Kellogg launched its low-energy nuclear astrophysics research program in 1946. Fowler's graduate student, R. N. Hall, took as his topic for a Ph.D. thesis the determination of the rates of the reactions in the carbon-nitrogen cycle at stellar conditions. Four years later, Fowler and Hall published their first paper on the problem.[13]

Hall's problems were considerable. First, it took time to build a low-energy Cockcroft-Walton-like accelerator to stimulate low, stellar energies. Even so, the terrestrial laboratory energies were too high, and extrapolation to lower energies unavoidable. The reactions, moreover, that Hall was after occur infrequently at low energies. Indeed, it took Hall three years just to accumulate 1000 positron tracks in the cloud chamber. In the sun, for example, the effective energy for the carbon-proton interaction measures only 30 kilovolts; the machine hall built in Kellogg was a low-energy 150 kilovolt machine -- this was the lowest energy the physicists could get in the laboratory and still detect something. In the end, Fowler and his students showed conclusively that the carbon-nitrogen cycle is not the dominant process in the sun.

To be sure, Bethe had also suggested another process, the proton-proton chain.[14] The measurements made in Kellogg supported the latter process, in which protons combine to form helium, with the emission of large amounts of energy. To the question: what does the sun shine on? Fowler's group decisively answered: the proton-proton chain. Kellogg researchers had conclusively resolved the first nuclear-astrophysical problem based on Bethe's pre-World War deductions.

ENDNOTES

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1. Extensive discussion on this point is provided in J. L. Greenberg and J. R. Goodstein, "Theodore von Kármán and Applied Mathematics in America," _Science_ (in press).

2. W. A. Fowler, "Phyphty Years of Phun and Physics in Kellogg," _Engineering and Science_, 1982, 45(4): 18-21, on p. 20.

3. Robert W. Seidel discusses in detail the work of the three laboratories in, "Physics Research in California: The Rise of a Leading Sector in American Physics (unpublished Ph.D. thesis, History, University of California, Berkeley, 1978), Part II.

4. Tuve to Slepian, 7 May 1937, Library of Congress, Tuve Papers.

5. Charles H. Holbrow, "The giant cancer tube and the Kellogg Radiation Laboratory," _Physics Today_, July 1981, 6-13.

6. L. R. Hafstad and M. A. Tuve, "Artificial Radioactivity Using Carbon Targets," _Physical Review_, 1934, 45:902-903; L. R. Hafstad and M. A. Tuve, "Induced Radioactivity Using Carbon Targets," _Physical Review_, 1935, 47:506.

7. Lawrence to Lauritsen, 9 February 1933, Bancroft Library, Lawrence Papers, C 10, f 36.

8. Lawrence to Tuve, 18 February 1933, 18 March 1933, Library of Congress, Tuve Papers; Tuve to Lauritsen, 29 March 1933, Caltech Archives, C. C. Lauritsen Papers, File 1.8.

9. William A. Fowler, "Nuclear Astrophysics -- Today and Yesterday," _Engineering and Science_, 1969, 32(9):8-13, on p. 8.

10. Ibid., p. 9.

11. H. A. Bethe, "Energy Production in Stars," _Physical Review_, 1939, 55:434-456.

12. Quoted in "William A. Fowler," transcript of an oral interview conducted by Charles Weiner, AIP, June 8 and 9, 1972, p. 39.

13. R. N. Hall and W. A. Fowler, "The Cross Section for the Radiative Capture of Protons by C^{12} near 100 Kev," _Physical Review_, 1950, 77:197-204.

14. H. A. Bethe and C. L. Critchfield, "The Formation of Deuterons by Proton Combination," _Physical Review_, 1938, 54:248-254.